NEW DEVELOPMENTS & APPLICATIONS FOR BODY MRI

Andrew Rosenkrantz MD
Associate Professor of Radiology and Urology
NYU Langone Medical Center

Andrew Rosenkrantz, MD NYULMC

Disclosures

- None

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Introduction

- DWI has become a standard sequence in body MRI protocols, largely for oncologic assessment
- Technical challenges related to EPI technique and variability in post-processing
- Opportunity for continued optimization:
  - Image acquisition
  - Data analysis

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Advances in DWI Acquisition

- Largely focus on:
  - Reducing anatomic distortion
  - Reducing artifacts
  - Reducing acquisition time
- Various strategies explored in body imaging:
  - Reduced-FOV imaging
  - Readout-segmented acquisition
  - Bipolar vs. monopolar refocusing schemes
  - Simultaneous multi-slice imaging

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Reduced-FOV DWI

- Focused excitation using 2D spatially-selective excitation pulses at a smaller FOV targeting organ of interest
- Elimination of wrap artifact that is encountered if simply reducing the FOV for a standard DWI sequence
- Achieves higher spatial resolution

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Reduced-FOV DWI

- Increased pixel bandwidth along phase-encoding direction
- Reduced-FOV greatly facilitated by 2-channel parallel transmission
- Sequence modifications using pTx allow reduced read-out length in PE-direction
  - Substantially shorter ETL
  - Reduced TE_{min}
  - Potentially increase SNR
  - Reduced distortion and artifacts

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Reduced-FOV DWI

- Most useful for small structures:
  - Prostate
  - Pancreas

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Reduced-FOV DWI: Prostate

- Thierfelder et al (Eur Radiol 2014)
  - Reduced distortions relative to T2WI
  - Reduced artifacts
  - Improved anatomic clarity
  - Improved agreement for prostate diameter/volume
  - Improved overall image quality
- Rosenkrantz et al (Abd Imaging 2014)
  - Reduced artifacts
  - Improved anatomic clarity
  - Improved overall image quality
- Suggested role in facilitating non-endorectal coil small-FOV imaging

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Reduced-FOV DWI: Pancreas

- Thierfelder et al (Eur J Radiol 2014)
  - Reduced artifacts
  - Improved visualization of pancreatic duct
  - Improved overall image quality
- Riffel et al (PLoS One 2014)
  - Less image blur
  - Less respiratory motion artifact
  - Improved delineation of pancreas
  - Improved diagnostic confidence
- Ma et al (MRI 2014)
  - More than 2x improvement in spatial resolution
  - Improved image quality

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Reduced-FOV DWI

- Longer time needed for 2D spatially-selective pulses
  - Potentially reduced SNR from longer minimum TE
  - However, partially offset by reduced readout length
- Potential impact on ADC values:
  - No impact on ADC values in four of five previously cited studies

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Readout-Segmented DWI

- Acquire k-space as multiple shots or segments along the readout direction
- Substantially reduced echo-train length and echo spacing within each segment
- 2D-navigator based reacquisition to correct for motion between segments with large phase errors and guide combining of segments
- Reduced artifacts and anatomic distortion
- Improved spatial resolution possible
- Suggested to be helpful by bone or gas interfaces (i.e., bowel loops)

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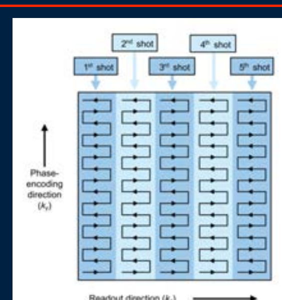
Readout-Segmented DWI



Porter DA and Heidermann RM. Magn Reson Med 2009.

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Readout-Segmented DWI: Pelvis

- Thian et al (Acad Radiology 2014)
  - Reduced blurring
  - Reduced artifacts
  - Improved lesion conspicuity
  - Improved overall image quality

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Readout-Segmented DWI: Liver

- Tokoro et al (Eur J Radiology 2014)
  - Showed feasibility and good image quality of free-breathing RS-DWI of the liver at reasonable scan time

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Readout-Segmented DWI: Breast

- Bogner et al (Radiology 2012)
  - Improved diagnostic accuracy
  - Improved lesion conspicuity
  - Improved image quality
  - Reduced anatomic distortions
- Bogner et al (Radiology 2014)
  - Performed at 7T
  - Subcentimeter resolution
  - Reduced distortion & blurring by factor of 7

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Readout-Segmented DWI

- Much slower readout of total k-space data
- Longer overall acquisition time
- May offset reduction in motion artifact
- Must consider tradeoffs to be clinically practical
  - Reduced anatomic coverage
  - Fewer b-values
  - Reduced averages
- Reduced SNR from higher spatial resolution

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Multi-band DWI

- Simultaneous acquisition of multiple slices (SMS)
- Composite RF pulse that simultaneously excites multiple slices
  - Signals superimposed in echo-train
- Apply multi-coil array and parallel imaging principles to individually reconstruct the excited slices
- More recently, use of tailored multi-band RF pulse with selective excitation of multiple slices that allows acceleration in the slice direction
  - Shorter TR and faster acquisition than earlier versions

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Multi-band DWI: Cardiac

- Lau AZ et al (MRM 2014):
  - Substantial time acceleration for multi-slice cardiac DTI
  - 9 breath-holds
  - Maintained high image quality

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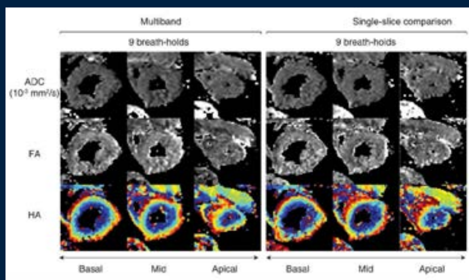
Multi-band DWI: Cardiac



Lau AZ et al. Magn Reson Med 2014

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Multi-band DWI: Liver

- Bhat H et al (ISMRM 2013):
  - 2x acceleration for liver DWI
  - Equivalent diagnostic quality and lesion conspicuity
  - Highly correlated ADC values

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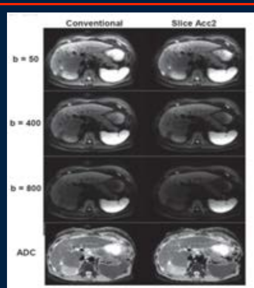
Multi-band DWI: Liver



Bhat H et al. ISMRM 2013 #0593

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Multi-band DWI

- Although some reduction in SNR, sequence remains relatively SNR-efficient
  - No reduction in echo train length as with partial Fourier or in-plane parallel acceleration methods that reduce sampling, so avoid √(N) SNR loss
  - SNR penalty less than through other methods to achieve comparable reduction in acquisition time for standard EPI DWI

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Monopolar vs. Bipolar DWI

- “Monopolar” DWI:
  - Single pair of gradients on either side of 180° refocusing pulse
- Commonly perform DWI with separate 180° refocusing pulses in encoding and decoding phases of the diffusion-encoding scheme
  - Described as “bipolar” encoding
  - Yields lobes of alternating polarity
  - Compensates for residual eddy currents

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Monopolar vs. Bipolar DWI

- Impact of bipolar scheme:
  - Reduced distortion
  - Longer TE due to second refocusing pulse
  - Lower SNR
- Recent investigations in literature regarding this trade-off
  - Bipolar scheme favored overall, but not in all studies

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Monopolar vs. Bipolar DWI

- Kyriazi et al (Eur Radiol 2010)
  - Bipolar improved distortion and led to overall higher image quality
- Rosenkrantz et al (Abd Imaging 2014)
  - Monopolar had higher overall image quality in liver
- Lewis et al (AJR 2015)
  - Equivalent image quality and lesion detection in liver
- Dyvorne et al. (Radiology 2013)
  - Comparable image quality in liver

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Advances in DWI Analysis

- Post-processing
  - Computed high b-value images
  - Advanced fitting models
- Measurements
  - Whole-lesion histogram analysis
    - Prostate, liver, pancreas, bladder

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Computed high b-value DWI

- Typically perform DWI using b-values up to approximately 1,000 sec/mm^2
- Higher b-value images suffer from reduced SNR and increased distortion
- Computed (extrapolated, synthesized) ultra high b-value images
  - Mathematically generated from standard b-value images, rather than directly acquired
  - Based on standard mono-exponential fit

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Computed high b-value DWI

- Provides image contrast of ultra high b-value images
- Good quality in terms of distortion and artifacts relative to truly acquired ultra high b-value images
- No additional acquisition time compared with that needed to acquire standard b-value images

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Computed high b-value DWI

- Most widely applied in prostate imaging
  - Mass MC et al (Invest Radiol 2013)
  - Ueno Y et al (Eur Radiol 2013)
  - Rosenkrantz AB et al (Eur Radiol 2013)
  - Bittencourt LK et al (World J Radiol 2014)
  - Vural M et al (Biomed Res Int 2014)
- Image quality and lesion detection consistently outperform acquired b1000 images and at least comparable to acquired higher b-values
- Formally acknowledged in ACR PI-RADS

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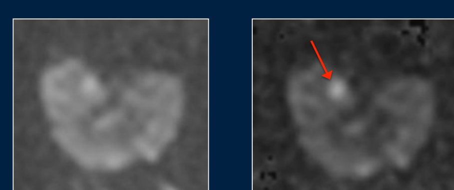
DWI: Computed high b-values



Acquired b1000 Extrapolated b1500

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Computed high b-value DWI

- Conceptual limitation that mono-exponential model used for extrapolation does not apply at ultra high b-values

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Diffusion Kurtosis Imaging

- Mono-exponential model no longer universally correct at b-values > 1,000
- SI decay plot no longer linear, but exhibits unique curvature, deviating from mono-exponential model
- Attributed to non-Gaussian water diffusion behavior
- DKI takes into account non-Gaussian water behavior at very high b-values

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Diffusion Kurtosis Imaging

•Standard mono-exponential model:
$S = S_0 \cdot e(-b \cdot \boldsymbol{ADC})$

•Non-Gaussian model:
$S = S_0 \cdot e\,[-bD + (1/6)b^2D^2\boldsymbol{K})]$

K: Diffusional kurtosis
Typically in range of 0-2
Higher value → Greater non-Gaussian behavior
Greater deviation from mono-exponential curve

D: diffusion coefficient corrected for the non-Gaussian behavior

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Diffusion Kurtosis Imaging

- ADC attributed to extracellular water diffusion
- K also believed to be, in part, impacted by intracellular compounds and exchange
- K increased in setting of more irregular and heterogeneous intracellular environments
  - For example, increased nuclear-cytoplasmic ratio

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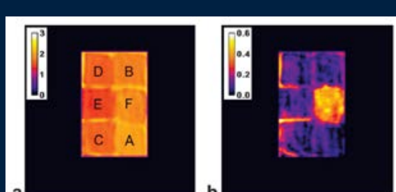
Diffusion Kurtosis Imaging



•A-E: Sucrose solutions of varying concentrations
•F: Pureed asparagus

Jensen JH et al. Magn Reson Med 2005

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Diffusion Kurtosis Imaging

- Acquisition using standard DWI sequence
- Requires a maximal b-value of at least 1,500 sec/mm², if not higher
- Sufficient SNR on maximal b-value images critical for reliable K estimates
  - Mathematical noise compensation advised
- Dedicated post-processing software required

Diffusion Kurtosis Imaging: Prostate

- For body imaging, most widely applied in prostate
- Improved differentiation of benign vs. malignant tissue:
  - Tamura C et al. (JMRI 2014)
  - Mazzoni LN et al (JMRI 2014)
  - Suo S et al (MRI 2014)
- Improved differentiation of low vs. high grade cancer
  - Rosenkrantz AB et al (Radiology 2012)
  - AUC of 0.70 for K compared with 0.62 for ADC

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Diffusion Kurtosis Imaging

- Breast (Wu D et al., PloS one 2014)
  - Improved accuracy for benign vs. malignant lesions using K
- Lung (Trampel R et al., MRM 2006)
  - K, but not ADC, showed alterations in small airway disease imaging using hyperpolarized helium
- Liver (Rosenkrantz AB et al, MRI 2014)
  - In ex-vivo liver explants, K positively correlated with tumor cellularity of HCC; K also reduced in necrotic treated HCC
- Bladder (Suo S et al. JCAT 2015)
  - Higher AUC of K than ADC for bladder cancer grade

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Whole-lesion Histogram Analysis

- In clinical practice, commonly measure ADC based on user-defined single-slice ROI
- Prone to sampling error, inter-observer variability, and incomplete representation of lesion
- Alternative use of whole-lesion histogram analysis:
  - 3D volume-of-interest encompassing entire lesion
  - Dedicated software for extracting histogram-based metrics

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Whole-lesion Histogram Analysis

- Complete lesion sampling
- Metrics that may be more sensitive to aggressive elements within tumor than mean or median ADC:
  - 10^{th} or 25^{th} percentile ADC
- Additional metrics assessing lesion texture and heterogeneity:
  - Kurtosis
  - Skewness
  - Entropy

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WL Histogram Analysis: Prostate

- ADC entropy (Rosenkrantz AB et al, JMRI 2014:
  - Outperformed standard mean ADC in characterizing Gleason 4 component in Gleason 7 cancer
- 10^{th} percentile ADC (Donati OF et al, Radiology 2014):
  - Stronger correlation with Gleason score at prostatectomy than mean or median ADC
- 10^{th} percentile ADC (Peng Y et al, Radiology 2013)
  - Independent variable from mean ADC in a highly accurate model for localizing cancer at prostatectomy

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WL Histogram Analysis: Other

- **Bladder** (Rosenkrantz AB et al Abd Imaging 2014):
  - Kurtosis, but not ADC, difference in bladder tumors with nodal and distant metastases
- **Bladder** (Suo ST et al., Acad Radiol 2014)
  - Combination of mean ADC and kurtosis achieved highest accuracy for separating benign and malignant lesions
- **Adnexa** (Kierans AS et al, JMRI 2013)
  - Entropy more accuracy than mean ADC for differentiating benign and malignant lesions

WL Histogram Analysis: Other

- **Cervical cancer** (Downey K et al, AJR 2013)
  - Skewness significantly less positive in adenocarcinoma than squamous cell carcinoms
- **Rectal cancer** (Cho Sh et al, Acta Radiol 2014)
  - 10th percentile ADC outperformed mean ADC in predicting complete pathologic response to chemoradiotherapy

Conclusion

- Various acquisition schemes studied for improving image quality or scan time of DWI
  - Some of the described methods require parallel transmission
  - Overall, small number of published studies validating methods in body imaging
  - Small-FOV DWI supported in pancreas and prostate
- DKI model provides novel parameter K, although further studies in the body required
- Whole-lesion histogram assessment supported for improved oncologic assessment in spectrum of pelvic tissues

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